AXIONS: RECENT SEARCHES AND NEW LIMITS*

GEORG G. RAFFELT
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
Föhringer Ring 6, 80805 München, Germany
E-mail: raffelt@mppmu.mpg.de

ABSTRACT

The CERN Axion Solar Telescope (CAST) experiment searches for solar axions by the "helioscope" method. First results imply an upper limit on the axion-photon coupling of $g_{a\gamma} < 1.16 \times 10^{-10}\ \mathrm{GeV}^{-1}$ (95% CL) for $m_a \lesssim 0.02$ eV, in this mass range superseding the previous energy-loss limit from globular cluster stars. By virtue of a variable-pressure helium filling of the magnetic transition region, CAST II will extend the sensitivity to axion masses up to about 1 eV, for the first time testing realistic axion parameters in a laboratory experiment. In this mass range axions would contribute a cosmic hot dark matter component. New structure-formation limits imply that $m_a < 1$–2 eV. For the particular case of hadronic axions with a standard axion-pion coupling, the present-day cosmic axion density would be about 50 cm^{-3} and the cosmic mass limit is $m_a < 1.05$ eV (95% CL). We also comment on the axion interpretation of the anomalous signature observed in the PVLAS experiment.

1. Introduction

Quantum chromodynamics is a CP-violating theory, implying that the neutron should have a large electric dipole moment, in conflict with the opposite experimental evidence. The most elegant solution of this "strong CP problem" was proposed by Peccei and Quinn (PQ) who showed that CP conservation is dynamically restored in the presence of a new global U(1) symmetry that is spontaneously broken at some large energy scale[3,4]. Weinberg[5] and Wilczek[6] realized that an inevitable consequence of the PQ mechanism is the existence of a new pseudoscalar boson, the axion, which is the Nambu-Goldstone boson of the PQ symmetry. This symmetry is explicitly broken at low energies by instanton effects so that the axion acquires a small mass. Unless there are non-QCD contributions, perhaps from Planck-scale physics[7,8], the mass is

$$m_a = \frac{z^{1/2}}{1+z}\,\frac{f_\pi m_\pi}{f_a} = \frac{6.0\ \mathrm{eV}}{f_a/10^6\ \mathrm{GeV}}\,, \tag{1}$$

where the energy scale f_a is the axion decay constant or PQ scale that governs all axion properties, $f_\pi = 93$ MeV is the pion decay constant, and $z = m_u/m_d$ is the mass ratio of the up and down quarks. We follow the previous axion literature and assume a value[9,10] $z = 0.56$, but note that it could vary in the range[11] 0.3–0.7.

*Based on work done in collaboration with K. Zioutas *et al.* (CAST Collaboration)[1] and with S. Hannestad and A. Mirizzi[2]. Contribution to Proc. XI International Workshop on "Neutrino Telescopes" (22–25 Feb 2005, Venice, Italy).

The PQ scale is constrained by various experiments and astrophysical arguments that involve processes where axions interact with photons, electrons, and hadrons[11,12]. The interaction strength with these particles scales as f_a^{-1}, but also includes significant uncertainties from model-dependent numerical factors. If axions indeed exist, experimental and astrophysical limits suggest[11,12] $f_a \gtrsim 0.6 \times 10^9$ GeV and $m_a \lesssim 0.01$ eV. The most restrictive of these limits depends on the axion-nucleon interaction that is constrained in two different ways by the observed neutrino signal of supernova (SN) 1987A[11,12]. The axionic energy loss caused by processes such as $NN \to NNa$ excludes a window of the axion-nucleon interaction strength where the axionic contribution to the loss or transfer of energy would have been comparable to or larger than that of neutrinos. For a sufficiently large interaction strength, axions no longer compete with neutrinos for the overall energy transfer in the SN core, but then would cause too many events in the water Cherenkov detectors that observed the neutrino signal. However, there is an intermediate range of couplings, corresponding to f_a around 10^6 GeV, i.e. to an axion mass of a few eV, where neither argument is conclusive. In this "hadronic axion window," these elusive particles could still exist[13,14] even if the SN 1987A limits are taken at face value. But of course, the SN 1987A limits rely on the model-dependent axion-nucleon coupling, they involve large statistical and systematic uncertainties, and perhaps unrecognized loop-holes. Therefore, it is prudent to consider other experimental or astrophysical methods to corner axions in this range of parameters.

In Sec. 2 we will report on recent results and future plans of the CAST experiment at CERN that searches for axions or axion-like particles emitted by the Sun. In Sec. 3 we will discuss the role of axions as dark matter and in particular new limits on hot dark matter axions. In Sec. 4 we will briefly comment on the axion interpretation of the anomalous signature found by the PVLAS experiment. In Sec. 5 we will summarize and conclude.

2. First results and future plans of the CAST experiment

The properties of axions are closely related to those of neutral pions. In particular, one generic property is a two-photon interaction of the form

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a\,, \tag{2}$$

where F is the electromagnetic field-strength tensor, $\tilde{F}$ its dual, and $\mathbf{E}$ and $\mathbf{B}$ the electric and magnetic field, respectively. The coupling constant is

$$g_{a\gamma} = -\frac{\alpha}{2\pi f_a} \left(\frac{E}{N} - \frac{2}{3}\, \frac{4+z}{1+z} \right)\,, \tag{3}$$

where E and N are the electromagnetic and color anomaly, respectively, of the axial current associated with the axion. In grand unified models such as the DFSZ

model[15,16] one has $E/N = 8/3$, but in general the value of E/N is not known so that for fixed f_a a broad range of $g_{a\gamma}$ values is possible[17]. In Fig. 1 we show $g_{a\gamma}$ as a function of m_a as a broad, shaded band that indicates a typical range for $g_{a\gamma}$ although, in principle, $g_{a\gamma}$ can take on almost any value for a given m_a. Still, the shaded band or "axion line" is the best-motivated region to search for axions.

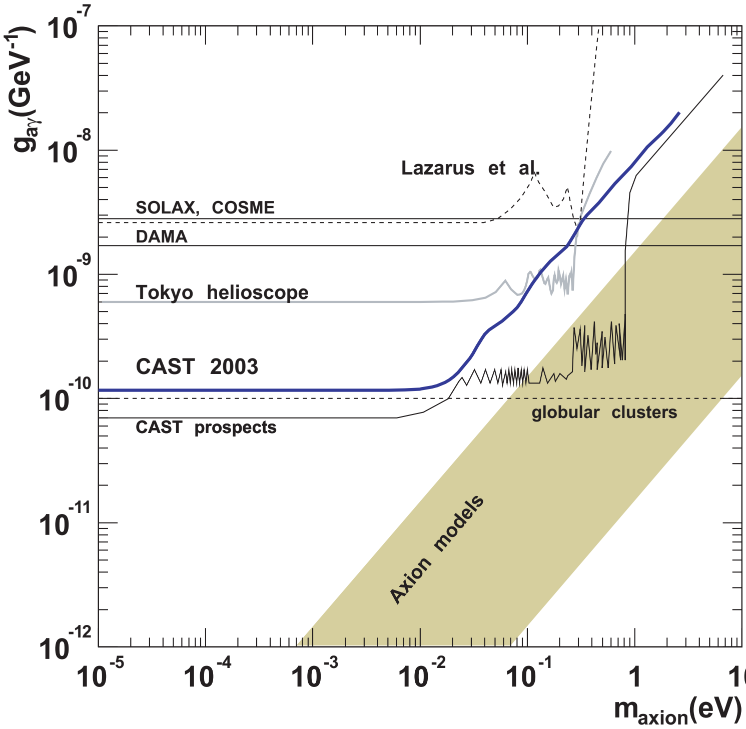

Figure 1: Exclusion limit (95% CL) from the CAST 2003 data compared with other constraints discussed in the text. The shaded band represents typical theoretical models. Also shown is the future CAST sensitivity as foreseen in the CAST proposal. (Figure from the CAST publication[1].)

Particles with a two-photon interaction, and this includes gravitons besides the hypothetical axions, can transform into photons in external electric or magnetic fields, an effect first discussed by Primakoff in the early days of pion physics[18]. Therefore, stars could produce these particles by transforming thermal photons in the fluctuating electromagnetic fields of the stellar plasma[19]. Calculating the expected solar axion flux is a straightforward exercise where the only difficulty is the proper inclusion of screening effects[20,21]. A calculation of the axion flux expected at Earth, based on a recent solar model[22], is shown in Fig. 2. A simple analytic fit formula is (Fig. 2)

$$\frac{d\Phi_a}{dE} = g_{10}^2 \; 6.020 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \left(\frac{E}{\text{keV}}\right)^{2.481} \exp\left(-\frac{E}{1.205 \text{ keV}}\right) , \qquad (4)$$

where $g_{10} = g_{a\gamma}/(10^{-10} \text{ GeV}^{-1})$. The flux uncertainty due to solar-model uncertainties is very small, perhaps a few percent.

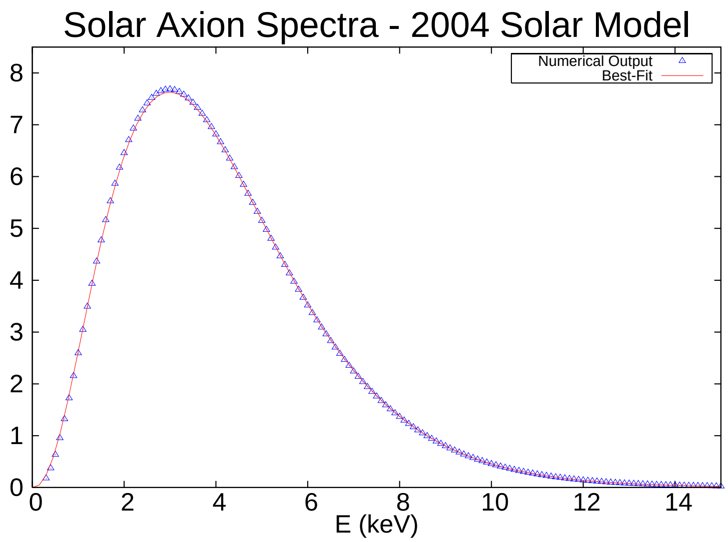

Figure 2: Axion flux from a modern solar model[22] (triangles) compared with the analytic fit Eq. (4).

In laboratory or astrophysical B-fields, particles with a two-photon vertex mix with photons so that these particles and photons "oscillate" much in the same way as neutrino flavor oscillations[23,24]. This phenomenon can be searched for in the laboratory[11], can affect the propagation of cosmic γ-rays[25,26], and can modify the apparent brightness of distant astronomical sources, in particular of SNe Ia that are used as standard candles to measure the Hubble diagram[27,28,29].

A particularly intriguing application of magnetically induced axion-photon conversions is to search for solar axions by an "axion helioscope" as proposed by Sikivie[23]. One would look at the Sun through a "magnetic telescope" and place an x-ray detector at the far end. The axion-photon conversion probability in a B-field is[23]

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma}B}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right) , \tag{5}$$

where L is the path length and q is the axion-photon momentum difference that in vacuum is $q = m_a^2/2E$. For $qL \lesssim 1$ the axion-photon oscillation length exceeds L. In the limit $qL \ll 1$ we have $P_{a\to\gamma} = (g_{a\gamma}BL/2)^2$, implying an x-ray flux of

$$\Phi_\gamma = 0.51\ \mathrm{cm}^{-2}\ \mathrm{day}^{-1}\, g_{10}^4 \left(\frac{L}{9.26\ \mathrm{m}}\right)^2 \left(\frac{B}{9.0\ \mathrm{T}}\right)^2 . \tag{6}$$

For $qL \gtrsim 1$ this rate is reduced due to the axion-photon momentum mismatch. A low-Z gas would provide a refractive photon mass m_γ so that $q = |m_\gamma^2 - m_a^2|/2E$. For $m_a \approx m_\gamma$ the maximum rate can thus be restored[31].

A first experiment of this sort was implemented at Brookhaven[30]. Later, a fully telescopic axion helioscope with $L = 2.3$ m and $B = 3.9$ T was built in Tokyo[32]. The absence of events above background implied $g_{10} < 6.0$ at 95% CL for $m_a \lesssim 0.03$ eV.

Later the m_a range was extended to almost 0.3 eV with a filling of helium gas at variable pressure, reaching limits in the range[33] $g_{10} < 6.8$–10.9 (Fig. 1). However, this experiment did not reach the "axion line."

Solar axions could also transform efficiently in electric crystal fields when the Bragg condition is satisfied[34]. However, the limits obtained by the dark matter experiments SOLAX in Sierra Grande[35], COSME in the Canfranc underground laboratory[36], and DAMA at Gran Sasso[37] are less restrictive than the Tokyo limit and they also require an unacceptably high solar axion luminosity[38].

In order to search for solar axions an axion helioscope was built at CERN by refurbishing a de-commissioned LHC test magnet[39] which produces a magnetic field of $B = 9.0$ T in the interior of two parallel pipes of length $L = 9.26$ m and a cross-sectional area $A = 2 \times 14.5$ cm^2. The aperture of each of the bores fully covers the potentially axion-emitting solar core of about one tenths of the solar radius. The magnet is mounted on a platform with $\pm 8^\circ$ vertical movement, allowing for observation of the Sun for 1.5 h at both sunrise and sunset. The horizontal range of $\pm 40^\circ$ encompasses nearly the full azimuthal movement of the Sun throughout the year. A full cryogenic station[40] is used to cool the superconducting magnet down to 1.8 K. The tracking system has been precisely calibrated by means of geometric survey measurements in order to orient the magnet to any given celestial coordinates. The overall CAST pointing precision is better than[41] 0.01°.

Three different detectors have searched for excess x-rays from axion conversion in the magnet when it was pointing to the Sun. Covering both bores of one of the magnet's ends, a conventional Time Projection Chamber is looking for x-rays from "sunset" axions. At the other end, facing "sunrise" axions, a smaller gaseous chamber with novel MICROMEGAS (micromesh gaseous structure)[42] readout is placed behind one of the magnet bores, while in the other one a focusing x-ray mirror telescope is working with a Charge Coupled Device (CCD) as the focal plane detector. Both the CCD and the x-ray telescope are prototypes developed for x-ray astronomy[43].

CAST operated for about 6 months from May to November in 2003. An important feature of the CAST data treatment is that the detector backgrounds are measured with about 10 times longer exposure during the non-alignment periods. These data are used to estimate and subtract the true experimental background during solar tracking. The non-observation of a signal above background in all three detectors leads to the exclusion range shown in Fig. 1, taken from the recent CAST publication[1]. In the mass range $m_a \lesssim 0.02$ eV the new limit (95% CL) is

$$g_{a\gamma} < 1.16 \times 10^{-10}\ \mathrm{GeV}^{-1}\,. \tag{7}$$

In this mass range the limit is mass-independent because the axion-photon oscillation length far exceeds the length of the magnet. The CAST limit is far more restrictive than any previous laboratory limit. It is comparable to the constraint obtained by the requirement that horizontal-branch stars in globular clusters do not lose too much energy in the form of axions[12] ("globular cluster" line in Fig. 1). This astrophysical

argument has not been developed to the point where it could be associated with a precise statistical and systematic confidence level. Therefore, in the relevant mass range the new CAST result supersedes the globular-cluster limit even though the two constraints are nominally comparable.

The data taken in 2004 have not yet been fully analyzed. However, the stable operation of the experiment allowed the CAST collaboration to take enough high-quality data to anticipate that the final sensitivity (Fig. 1) will be close to the one projected in the CAST proposal.

The existing CAST limits and foreseen sensitivity with the 2004 data do not yet touch the "axion line" in Fig. 1. In Phase II the experiment will be modified to allow for a variable-pressure helium filling of the magnet's bores to provide the photons with an effective mass. The vapor pressure of He^4 at 1.8 K, the magnet's operating temperature, is such that a maximum axion mass of 0.26 eV can be reached. The pressure settings will be incremented in steps to achieve overlapping resonant sensitivity curves for different mass values. Using He^3 that has a higher vapor pressure, one can reach a higher axion mass of up to 0.8 eV. Reaching yet higher masses will require an isolating gas cell in the bore where He^3 at 5.4 K would allow one to reach a mass of 1.4 eV. The sensitivity forecast of CAST II is also indicated in Fig. 1. For the first time, a laboratory experiment will be able to probe the theoretically motivated range of axion parameters.

3. Axions as dark matter

Intriguingly, axions with a mass in the eV range as probed by CAST II would contribute a cosmic hot dark matter component much like neutrinos in this mass range. Of course, the exact cosmic number density of axions depends on their primordial freeze-out epoch. However, assuming that they freeze out after the QCD epoch, their number density relative to a single neutrino degree of freedom will not be diluted very much. Therefore, the usual cosmological structure-formation limits to neutrino masses[44] can be generalized to other particles that where once in thermal equilibrium[45] and particularly to axions[2].

For any particle that thermally decouples in the early universe when it is still relativistic, the present-day number density depends only on the number g_{*S} of effective cosmic thermal degrees of freedom contributing to the entropy density at the decoupling epoch. As the universe cools, the entropy of the interacting species eventually ends up in the cosmic microwave photons and in neutrinos, heating these species relative to the one that is already frozen out[46]. For a boson with a single spin degree of freedom, the present-day number density is

$$n_a = \frac{g_{*S}(\text{today})}{g_{*S}(\text{decoupling})} \times \frac{n_\gamma}{2}\,, \tag{8}$$

where $n_\gamma = 411\ \mathrm{cm}^{-3}$ is the present-day density of cosmic microwave photons and today[46] $g_{*S} = 3.91$. For cosmic epochs before neutrino decoupling, the effective

number of thermal degrees of freedom g_* characterizing the energy density and g_{*S} for the entropy density are almost identical so that henceforth we will not distinguish between the two quantities.

Once the decoupling epoch for the new particles has been established, their number density and velocity dispersion are known so that one can determine if the corresponding hot dark matter fraction is compatible with the usual large-scale structure and cosmic microwave background radiation data. In Fig. 3 we show the allowed range for m_a and g_* from the analysis of Hannestad, Mirizzi and Raffelt[2)].

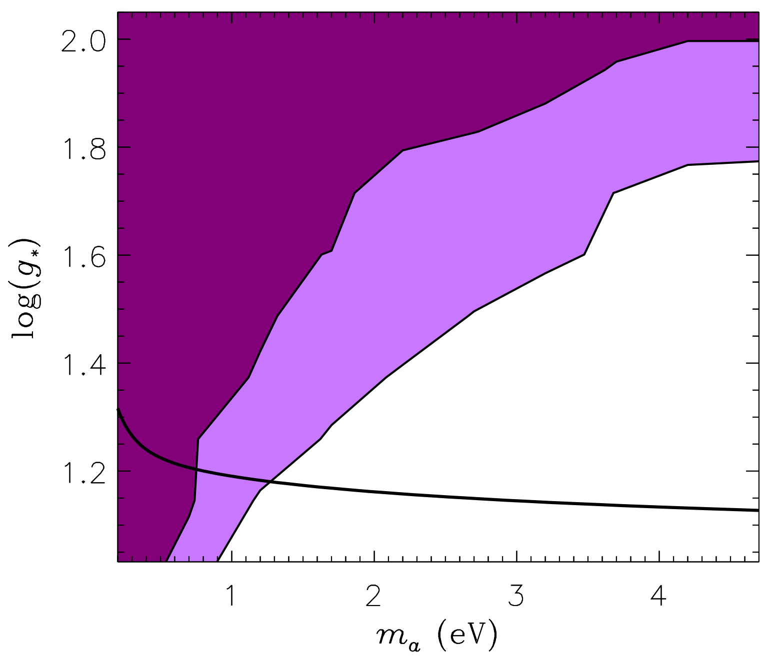

Figure 3: Likelihood contours for the cosmologically allowed axion mass m_a and g_*, the number of effective cosmic thermal degrees of freedom at the epoch of axion decoupling. Everything to the right of the dark shaded region is excluded at the 68% CL, and everything to the right of the light shaded region is excluded at the 95% CL. The relation between g_* and m_a for hadronic axions is shown as a thick solid line. (Figure from Hannestad, Mirizzi and Raffelt[2)].)

At the time of neutrino decoupling at a temperature of about 1 MeV, only photons, electrons and neutrinos contribute to the cosmic radiation density so that $g_* = 10.75$. At higher temperatures, muons, pions and other mesons begin to contribute so that g_* increases to about 23 at $T_{\rm QCD} \approx 150$ MeV when the color deconfinement transition occurs, causing a fast increase of g_* to about 100 for $T > T_{\rm QCD}$. Therefore, if axions thermally decouple after the QCD epoch, their mass can not exceed 1–2 eV to avoid too much free-streaming erasure of small scale structure in the universe.

If we consider new axion-like particles that have no other interactions at low energies besides the two-photon vertex, we can estimate their freeze-out temperature by the simple criterion that their interaction rate Γ should exceed the cosmic expansion rate H. On dimensional grounds we have $H \sim T^2/m_{\rm Pl}$ with $m_{\rm Pl} = 1.2 \times 10^{19}$ GeV

the Planck mass and $\Gamma \sim g_{a\gamma}^2 T^3$. Therefore, $\Gamma \sim H$ implies $T_{\rm decoupling} \sim g_{a\gamma}^{-2} m_{\rm Pl}^{-1}$. With $g_{a\gamma} \lesssim 10^{-10}~{\rm GeV}^{-1}$ we have $T_{\rm decoupling} \gtrsim 10~{\rm GeV} \gg T_{\rm QCD}$ and thus $g_* > 100$–200 at decoupling. Therefore, we have no substantial mass limit on such particles.

Turning to realistic models in the context of the PQ mechanism, axions generically interact with hadrons, even though the exact coupling constants are model dependent. In particular, the axion-pion interaction is of the form[13]

$$\mathcal{L}_{a\pi} = \frac{C_{a\pi}}{f_\pi f_a} \left(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0\right) \partial_\mu a\,. \tag{9}$$

In hadronic axion models where the ordinary quarks and leptons do not carry PQ charges, the coupling constant is[13]

$$C_{a\pi} = \frac{1-z}{3\,(1+z)}\,. \tag{10}$$

In non-hadronic models an additional term enters that could reduce $C_{a\pi}$.

Assuming the hadronic axion-pion interaction strength, the decoupling temperature and the corresponding g_* was calculated on the basis of the dominant $\pi\pi \leftrightarrow \pi a$ processes[2,13]. Assuming in addition the standard m_a-f_a relation of Eq. (1), hadronic axions live on the thick solid line shown in Fig. 3. In this case the axion parameter space collapses to one dimension, i.e. the cosmological maximum likelihood analysis involves only a single independent axion parameter. In this case one finds[2]

$$\begin{aligned} m_a &< 1.05~{\rm eV}\,, \\ f_a &> 5.7\times10^6~{\rm GeV} \end{aligned} \tag{11}$$

at 95% CL. The present-day cosmic axion density would be about 50 cm^{-3}. For comparison we note that the same method provides[47] $\sum m_\nu < 0.65$ eV at 95% CL. It is understood that these constraints involve a number of well-recognized systematic uncertainties inherent in the underlying cosmological assumptions.

Axions are an often-cited cold dark matter candidate if they interact so weakly (if f_a is so large) that they never achieve thermal equilibrium[48,49,50,51]. In that case coherent oscillations of the axion field are excited around the QCD transition when the PQ symmetry is explicitly broken by instanton effects. The mass range where axions would contribute the cosmic cold dark matter is fairly uncertain but probably is somewhere in the range[11] $1~\mu{\rm eV} < m_a < 1$ meV. Galactic dark matter axions in the lower range of these plausible masses are searched for by the well-known microwave cavity experiments[52]. The main point for our present discussion is that axions, depending on their mass, can contribute to the cosmic cold dark matter or the hot dark matter. It is important to note that very low-mass axions would be cold dark matter, whereas eV-mass axions would be a hot dark matter component. This situation is opposite for neutrino-like particles (WIMPs) that contribute to the hot dark matter for eV-range masses whereas they are cold dark matter typically with masses beyond several tens of GeV. The key difference to axions is that axions can

be a cold dark matter candidate only if they never reached thermal equilibrium and thus would survive as a non-thermal relic.

If CAST II were to detect axions in the sub-eV mass range, these particles would contribute a new hot dark matter component in addition to the one provided by ordinary neutrinos. At the same time axions would then be excluded as a candidate for cold dark matter.

4. Axion interpretation of the PVLAS signature?

Another possibility to search for particles with a two-photon vertex is their effect on the propagation of a laser beam in the presence of a transverse magnetic field. The photon state polarized perpendicularly to **B** remains unaffected whereas the parallel one undergoes partial photon-axion oscillations. As a result, a potentially measurable effect on the overall polarization of the laser beam occurs[53,24]. The PVLAS experiment[54] is an ongoing effort to search for this effect. Intriguingly, a strong effect has been observed that at present can not be ascribed to any known instrumental factors and thus could be indicative of new physics.

One tentative interpretation is that PVLAS may actually be observing axion-like particles. The required axion-photon coupling strength is around 3×10^{-6} GeV^{-1} and thus much larger than what is allowed by either the CAST limits, the globular-cluster constraint, or simply the observed properties of our Sun[38]. In that sense CAST does not directly rule out the PVLAS effect because CAST relies on the standard Sun as a source where axion emission is only a small effect. We note that the solar axion luminosity due to the Primakoff effect is $L_a = g_{10}^2\, 1.7 \times 10^{-3}\, L_\odot$ so that the PVLAS-suggested value for $g_{a\gamma}$ implies an axion luminosity about a million times larger than the solar photon luminosity. Such a large effect can not be accommodated in a self-consistent solar model and in any case, the Sun would consume its nuclear fuel a million times faster and could only exist for a few thousand years.

One may think that this argument can be circumvented by assuming that the PVLAS-particles interact so strongly in some reaction channel that they can not freely escape from the Sun. This assumption, however, does not provide a viable loop hole. Even if the particles can not freely escape, they will still contribute to the transfer of energy within the Sun and thus strongly affect the Sun's structure and its speed of energy loss. A low-mass particle would be harmless only if its interaction cross section is either so small that it does not carry away too much energy or else more strongly interacting than electromagnetic strength to avoid excessive energy transfer in the Sun[55]. In this latter case presumably it would not have escaped experimental detection.

Therefore, the axion interpretation of the PVLAS signature does not appear viable unless one can come forth with a self-consistent mechanism that avoids excessive energy loss or energy transfer in the Sun and other stars. A first attempt to construct a particle-physics model for the PVLAS signature and yet avoids the solar energy transfer argument has just been reported[57]. If it is viable remains to be discussed.

5. Summary

First results from the CAST experiment, based on the 2003 data, provide a new limit on the two-photon vertex of axions or other similar hypothetical particles. In the mass range $m_a \lesssim 0.02$ eV the new limit supersedes the previous globular-cluster constraint. The 2004 data will provide significantly improved sensitivity. In phase II, CAST will use a variable-pressure buffer gas in the magnetic transition region to increase its sensitivity to axion masses up to around 1 eV. If axions were discovered in this mass range they would contribute a cosmic hot dark matter component in addition to ordinary neutrinos. Conversely, structure-formation limits imply that hot dark matter axions should obey an upper mass limit of 1–2 eV, depending on the exact axion-pion interaction strength. The axion interpretation of the PVLAS experiment does not appear viable in view of the properties of our Sun. Therefore, the search for axions continues, both by the CAST experiment for solar axions and by the cavity searches for galactic cold dark matter axions.

6. Acknowledgments

I thank my collaborators in the works described here, i.e. K. Zioutas *et al.* (CAST Collaboration)[1)] and S. Hannestad and A. Mirizzi[2)]. Partial support by the Deutsche Forschungsgemeinschaft under grant No. SFB 375 and by the European Union under the Ilias project, contract No. RII3-CT-2004-506222, is acknowledged.

7. References

1) K. Zioutas *et al.* (CAST Collaboration), "First results from the CERN axion solar telescope (CAST)," Phys. Rev. Lett. **94** (2005) 121301 [hep-ex/0411033]. See also: http://cast.web.cern.ch/CAST/
2) S. Hannestad, A. Mirizzi and G. Raffelt, "New cosmological mass limit on thermal relic axions," hep-ph/0504059.
3) R. D. Peccei and H. R. Quinn, "CP Conservation in the presence of pseudoparticles," Phys. Rev. Lett. **38** (1977) 1440.
4) R. D. Peccei and H. R. Quinn, "Constraints imposed by CP conservation in the presence of pseudoparticles," Phys. Rev. D **16** (1977) 1791.
5) S. Weinberg, "A new light boson?," Phys. Rev. Lett. **40** (1978) 223.
6) F. Wilczek, "Problem of strong P and T invariance in the presence of instantons," Phys. Rev. Lett. **40** (1978) 279.
7) M. Kamionkowski and J. March-Russell, "Planck scale physics and the Peccei-Quinn mechanism," Phys. Lett. B **282** (1992) 137 [hep-th/9202003].
8) S. M. Barr and D. Seckel, "Planck scale corrections to axion models," Phys.

Rev. D **46** (1992) 539.

9) J. Gasser and H. Leutwyler, "Quark masses," Phys. Rept. **87** (1982) 77.
10) H. Leutwyler, "The ratios of the light quark masses," Phys. Lett. B **378** (1996) 313 [hep-ph/9602366].
11) S. Eidelman *et al.* (Particle Data Group), "Review of particle physics," Phys. Lett. B **592** (2004) 1.
12) G. G. Raffelt, "Particle physics from stars," Annu. Rev. Nucl. Part. Sci. **49** (1999) 163 [hep-ph/9903472].
13) S. Chang and K. Choi, "Hadronic axion window and the big bang nucleosynthesis," Phys. Lett. B **316** (1993) 51 [hep-ph/9306216].
14) T. Moroi and H. Murayama, "Axionic hot dark matter in the hadronic axion window," Phys. Lett. B **440** (1998) 69 [hep-ph/9804291].
15) A. R. Zhitnitsky, "On possible suppression of the axion hadron interactions," Sov. J. Nucl. Phys. **31** (1980) 260 [Yad. Fiz. **31** (1980) 497].
16) M. Dine, W. Fischler and M. Srednicki, "A simple solution to the strong CP problem with a harmless axion," Phys. Lett. B **104** (1981) 199.
17) S. L. Cheng, C. Q. Geng and W. T. Ni, "Axion-photon couplings in invisible axion models," Phys. Rev. D **52** (1995) 3132 [hep-ph/9506295].
18) H. Primakoff, "Photo-production of neutral mesons in nuclear electric fields and the mean life of the neutral meson," Phys. Rev. **81** (1951) 899.
19) D. A. Dicus, E. W. Kolb, V. L. Teplitz and R. V. Wagoner, "Astrophysical bounds on the masses of axions and Higgs particles," Phys. Rev. D **18** (1978) 1829.
20) G. G. Raffelt, "Astrophysical axion bounds diminished by screening effects," Phys. Rev. D **33** (1986) 897.
21) T. Altherr, E. Petitgirard and T. del Río Gaztelurrutia, "Axion emission from red giants and white dwarfs," Astropart. Phys. **2** (1994) 175 [hep-ph/9310304].
22) J. N. Bahcall and M. H. Pinsonneault, "What do we (not) know theoretically about solar neutrino fluxes?," Phys. Rev. Lett. **92** (2004) 121301 [astro-ph/0402114]. See also http://www.sns.ias.edu∼jnb/SNdata/sndata.html
23) P. Sikivie, "Experimental tests of the invisible axion," Phys. Rev. Lett. **51** (1983) 1415. Erratum *ibid.* **52** (1984) 695.
24) G. Raffelt and L. Stodolsky, "Mixing of the photon with low mass particles," Phys. Rev. D **37** (1988) 1237.
25) D. S. Gorbunov, G. G. Raffelt and D. V. Semikoz, "Axion-like particles as ultrahigh-energy cosmic rays?," Phys. Rev. D **64** (2001) 096005 [hep-ph/0103175].
26) C. Csaki, N. Kaloper, M. Peloso and J. Terning, "Super-GZK photons from photon axion mixing," JCAP **0305** (2003) 005 [hep-ph/0302030].
27) C. Csaki, N. Kaloper and J. Terning, "Dimming supernovae without cosmic acceleration," Phys. Rev. Lett. **88** (2002) 161302 [hep-ph/0111311].
28) B. A. Bassett, "Cosmic acceleration vs axion photon mixing," Astrophys. J.

607 (2004) 661 [astro-ph/0311495].
29) L. Ostman and E. Mörtsell, "Limiting the dimming of distant type Ia supernovae," JCAP **0502** (2005) 005 [astro-ph/0410501].
30) D. M. Lazarus, G. C. Smith, R. Cameron, A. C. Melissinos, G. Ruoso, Y. K. Semertzidis and F. A. Nezrick, "A search for solar axions," Phys. Rev. Lett. **69** (1992) 2333.
31) K. van Bibber, P. M. McIntyre, D. E. Morris and G. G. Raffelt, "A practical laboratory detector for solar axions," Phys. Rev. D **39** (1989) 2089.
32) S. Moriyama, M. Minowa, T. Namba, Y. Inoue, Y. Takasu and A. Yamamoto, "Direct search for solar axions by using strong magnetic field and x-ray detectors," Phys. Lett. B **434** (1998) 147 [hep-ex/9805026].
33) Y. Inoue, T. Namba, S. Moriyama, M. Minowa, Y. Takasu, T. Horiuchi and A. Yamamoto, "Search for sub-electronvolt solar axions using coherent conversion of axions into photons in magnetic field and gas helium," Phys. Lett. B **536** (2002) 18 [astro-ph/0204388].
34) E. A. Paschos and K. Zioutas, "A Proposal for solar axion detection via Bragg scattering," Phys. Lett. B **323** (1994) 367.
35) F. T. Avignone *et al.* (SOLAX Collaboration), "Experimental search for solar axions via coherent Primakoff conversion in a germanium spectrometer," Phys. Rev. Lett. **81** (1998) 5068. [astro-ph/9708008].
36) A. Morales *et al.* (COSME Collaboration), "Particle dark matter and solar axion searches with a small germanium detector at the Canfranc underground laboratory," Astropart. Phys. **16** (2002) 325 [hep-ex/0101037].
37) R. Bernabei *et al.*, "Search for solar axions by Primakoff effect in NaI crystals," Phys. Lett. B **515** (2001) 6.
38) H. Schlattl, A. Weiss and G. Raffelt, "Helioseismological constraint on solar axion emission," Astropart. Phys. **10** (1999) 353 [hep-ph/9807476].
39) K. Zioutas *et al.*, "A decommissioned LHC model magnet as an axion telescope," Nucl. Instrum. Meth. A **425** (1999) 480 [astro-ph/9801176].
40) K. Barth *et al.*, "Commissioning and first operation of the cryogenics for the CERN Axion Solar Telescope (CAST)," Proc. 2003 Cryogenic Engineering Conference (CEC) and Cryogenic Materials Conference (ICMC).
41) http://cast.web.cern.ch/CAST/edited_tracking.mov
42) Y. Giomataris, P. Rebourgeard, J. P. Robert and G. Charpak, "MICROMEGAS: A high-granularity position-sensitive gaseous detector for high particle-flux environments," Nucl. Instrum. Meth. A **376** (1996) 29.
43) J. Altmann *et al.*, in *Proceedings of SPIE: X-Ray Optics, Instruments, and Mission*, 1998, edited by Richard B. Hoover and Arthur B. Walker, p. 350; J. W. Egle *et al.*, *ibid.*, p. 359; P. Friedrich *et al.*, *ibid.*, p. 369.
44) S. Hannestad, "Neutrinos in cosmology," New J. Phys. **6**, 108 (2004) [hep-ph/0404239].
45) S. Hannestad and G. Raffelt, "Cosmological mass limits on neutrinos, axions, and other light particles," JCAP **0404** (2004) 008 [hep-ph/0312154].

46) E. W. Kolb and M. S. Turner, *The Early Universe* (Addison Wesley, 1990).
47) S. Hannestad, “Cosmological bounds on masses of neutrinos and other thermal relics,” contributed to the Proc. of SEESAW25: International Conference on the Seesaw Mechanism and the Neutrino Mass, Paris, France, 10–11 June 2004 [hep-ph/0409108].
48) J. Preskill, M. B. Wise and F. Wilczek, “Cosmology of the invisible axion,” Phys. Lett. B **120** (1983) 127.
49) L. F. Abbott and P. Sikivie, “A cosmological bound on the invisible axion,” Phys. Lett. B **120** (1983) 133.
50) M. Dine and W. Fischler, “The not-so-harmless axion,” Phys. Lett. B **120** (1983) 137.
51) R. L. Davis, “Cosmic axions from cosmic strings,” Phys. Lett. B **180** (1986) 225.
52) R. Bradley *et al.*, “Microwave cavity searches for dark-matter axions,” Rev. Mod. Phys. **75** (2003) 777.
53) L. Maiani, R. Petronzio and E. Zavattini, “Effects of nearly massless, spin zero particles on light propagation in a magnetic field,” Phys. Lett. B **175** (1986) 359.
54) G. Cantatore *et al.*, presented at IDM 2004, Edinburgh, England, 4–10 Sep. 2004. See http://www.shef.ac.uk/physics/idm2004/talks/friday/pdfs/cantatore_giovanni.pdf
55) G. G. Raffelt and G. D. Starkman, “Stellar energy transfer by kev mass scalars,” Phys. Rev. D **40** (1989) 942.
56) E. D. Carlson and P. Salati, “Stellar limits on kev pseudoscalars,” Phys. Lett. B **218** (1989) 79.
57) E. Masso and J. Redondo, “Evading astrophysical constraints on axion-like particles,” arXiv:hep-ph/0504202.